The Tau Neutrino as the
Lightest Supersymmetric Particle

$(\nu_\tau = \mathrm{LSP})$

Ernest Ma

Department of Physics, University of California, Riverside, CA 92521
and
Department of Physics, University of Wisconsin, Madison, WI 53706

Abstract

Given the conservation of baryon number as well as electron and muon numbers, all present data can be explained without the need of a conserved quantum number for the tau lepton and its neutrino. A supersymmetric extension of the standard model naturally allows for such a scenario. One consequence is that the tau neutrino becomes the lightest supersymmetric particle.

1. Introduction

It is usually thought that present experimental data indicate that baryon number (B), electron number (L^e), muon number (L$^\mu$), and tau number (L$^\tau$) should be taken as conserved quantum numbers, at least to a very good approximation. Actually, if we assume the conservation of B, L^e, and L$^\mu$, then there is no need for L$^\tau$. For example, the fact that in neutrino interactions on nuclei, τ leptons are not produced is explained by the conservation of L^e and L$^\mu$. Analogously, the fact that τ does not decay into an antiproton + mesons requires only the conservation of B.

The reason that L$^\tau$ appears to be conserved is that given the standard SU(2) × U(1) electroweak gauge model with its minimal particle content, the conservation of B, L^e, L$^\mu$, and L$^\tau$ is automatic. An excursion beyond the standard model is necessary to see how L$^\tau$ may be different from L^e and L$^\mu$.

2. Supersymmetric Standard Model

Consider for example any supersymmetric extension of the standard model. In a notation where only left chiral superfields are counted, the quarks and leptons transform under SU(3) × SU(2) × U(1) as follows:

$$Q \equiv (u, d)_{\mathrm{L}} \sim (3, 2, 1/6), \quad u^c \sim (\overline{3}, 1, -2/3), \quad d^c \sim (\overline{3}, 1, 1/3), \tag{1}$$

$$L \sim (\nu_\ell, \ell)_{\mathrm{L}} \sim (1, 2, -1/2), \quad \ell^c \sim (1, 1, 1). \tag{2}$$

The Higgs superfields are

$$\Phi_1 \sim (1, 2, -1/2), \quad \Phi_2 \sim (1, 2, 1/2). \tag{3}$$

The allowed terms in the superpotential are then

$$\Phi_1 \Phi_2, \quad \Phi_1 Q_i d_j^c, \quad \Phi_2 Q_i u_j^c, \quad \Phi_1 L_i \ell_i^c;$$

and

$$L_i\Phi_2, \quad L_iQ_jd_k^c, \quad L_iL_j\ell_k^c, \quad u_i^cd_j^cd_k^c.$$

Whereas the first four terms conserve B, L^e, L^μ, and L^τ, the above four do not and they are usually just ignored. What this amounts to is the imposition of B, L^e, L^μ, and L^τ as conserved quantum numbers.

Instead of forbidding all possible combinations of the last four terms, it is just as natural to forbid some of them, resulting in the conservation of one or two lepton numbers. It has been shown[1] that there are 5×3 ways of doing this, as given below.

Model	e	μ	τ
1	$(1,0)$	$(0,1)$	$(0,0)$
2	$(1,0)$	$(0,1)$	$(1,1)$
3	1	-1	0
4	1	1	0
5	1	0	0

Here the lepton-number assignments (L^e, L^μ) are displayed for models 1 and 2, and L for models 3-5. For each model, there are of course three possible variations resulting from the permutations of e, μ, and τ.

3. Zero Lepton Number for τ

If τ is to have zero lepton number, then Model 1 is the prototype.[2] The superpotential is given by

$$
\begin{aligned}
W &= \mu\Phi_1\Phi_2 + h_i\Phi_1L_i\ell_i^c + h_{ij}^u\Phi_2Q_iu_j^c + h_{ij}^d\Phi_1Q_id_j^c \\
&+ \mu'L_3\Phi_2 + f_eL_3L_1\ell_1^c + f_\mu L_3L_2\ell_2^c + f_{ij}L_3Q_id_j^c,
\end{aligned} \tag{4}
$$

where the coupling matrix h_i has been chosen to be diagonal. It reduces to the conventional supersymmetric model in the limit f_e, f_μ, f_{ij}, and μ' go to zero. The neutralino mass matrix spanning the gauginos $(-i\lambda_\gamma, -i\lambda_z)$, the higgsinos (ψ_1^0, ψ_2^0), and ν_3 is then

$$
\mathcal{M} =
\begin{bmatrix}
c^2 M_1 + s^2 M_2 & sc(M_2 - M_1) & 0 & 0 & 0 \\
sc(M_2 - M_1) & s^2 M_1 + c^2 M_2 & M_Z \cos\beta & -M_Z \sin\beta & 0 \\
0 & M_Z \cos\beta & 0 & -\mu & 0 \\
0 & -M_Z \sin\beta & -\mu & 0 & -\mu' \\
0 & 0 & 0 & -\mu' & 0
\end{bmatrix},
\tag{5}
$$

where $c \equiv \cos\theta_W$, $s \equiv \sin\theta_W$, $\tan\beta \equiv v_2/v_1 = \langle\phi_2^0\rangle/\langle\phi_1^0\rangle$, and $M_{1,2}$ are allowed gauge-invariant mass terms for the U(1) and SU(2) gauginos. As a result, the physical ν_τ is mostly ν_3, but there is a small admixture of the other states so that it acquires a small see-saw Majorana mass

$$
m_{\nu_\tau} \sim \frac{\mu'^2}{2\mu \tan\beta}.
\tag{6}
$$

For $\mu \sim 1$ TeV, $\tan\beta \sim 10$, $\mu' \sim 10$ MeV, an interesting value of 5 eV is obtained for m_{ν_τ}.

In the conventional supersymmetric model without the μ' term, the smallest eigenvalue of the 4×4 neutralino mass matrix is that of the lightest supersymmetric particle (LSP) and since R parity, defined to be $(-1)^{2j+3B+L}$, is conserved in that case, the LSP is absolutely stable. This has very important implications for the experimental search for supersymmetry because the LSP would be a weakly interacting particle which leaves the detector unobserved except that it carries away momentum and energy. Here, it is clear that ν_τ is the LSP, so that any of the other neutralinos such as the photino $\tilde{\gamma}$ (*i.e.* $-i\lambda_\gamma$) would decay through a scalar electron for example into $e^+ e^- \nu_\tau$ and might not remain stable within the detector in a typical high-energy physics experiment.

4. Phenomenological Constraints and Implications

The existence of the $L_3 Q_i d_j^c$ term is a source of tree-level flavor-changing neutral currents. The most stringent constraints come from the neutral kaons. The magnitude of the $K_L - K_S$ mass difference implies

$$|f_{sd} f_{ds}^*|^{\frac{1}{2}} < 10^{-4} \left(\frac{m_{\tilde{\nu}_\tau}}{100 \text{ GeV}} \right), \tag{7}$$

and the $K_L \to \mu^+ \mu^-$ rate implies

$$|f_\mu|^{\frac{1}{2}} \left(|f_{sd}|^2 + |f_{ds}|^2 \right)^{\frac{1}{4}} < 5 \times 10^{-4} \left(\frac{m_{\tilde{\nu}_\tau}}{100 \text{ GeV}} \right). \tag{8}$$

The possible deviation from zero of the Michel parameter η in $\mu \to e\nu\bar{\nu}$ decay implies

$$|\mathrm{Re} f_\mu f_e^*|^{\frac{1}{2}} < 0.11 \left(\frac{m_{\tilde{\tau}_L}}{100 \text{ GeV}} \right). \tag{9}$$

The parameters ρ and δ remain at 0.75 as in the standard model.

Since the nonconservation of L^τ is only achieved here with the intervention of supersymmetry, possible tests of this model will likely involve the direct production of supersymmetric particles. The best case is [2]

$$p\bar{p} \text{ (or } pp) \to \tau^\pm \tau^\pm + 2 \text{ quark jets,}$$

which involves (for the $\tau^+ \tau^+$ mode) the subprocesses $u\bar{d} \to \tilde{u}_L \tilde{d}_R^*$ through gluino exchange and their subsequent decay into $d\tau^+$ and $\bar{u}\tau^+$ respectively. The analogous reaction for an electron-proton collider is

$$ep \to \tau^- \tau^- + 1 \text{ quark jet} + \text{missing energy,}$$

which proceeds via the production of $\tilde{e}_R \tilde{d}_R$ and their subsequent decay into $\nu_e \tau^-$ and $u\tau^-$ respectively.

5. Conclusion

If supersymmetry exists, the issue of lepton number conservation will have to be reexamined experimentally. The conventional wisdom that L is conserved additively (or multiplicatively if neutrinos have Majorana masses) may not be correct. An interesting possibility would be that τ is actually a nonleptonic superparticle and

$$\boxed{\nu_\tau = \text{LSP}}$$

References

[1] E. Ma and D. Ng, *Phys. Rev.* **D41**, 1005 (1990).

[2] E. Ma and P. Roy, *Phy. Rev.* **D41**, 988 (1990).